THE CONTRIBUTION OF PRIMORDIAL BINARIES TO THE BLUE STRAGGLER POPULATION IN 47 TUCANAE

Michela Mapelli[1], Steinn Sigurdsson[2], Monica Colpi[3], Francesco R. Ferraro[4], Andrea
Possenti[5], Robert T. Rood[6], Alison Sills[7] & Giacomo Beccari[4]
Draft version February 2, 2008

ABSTRACT

The recent observation (Ferraro et al. 2003b) of the blue straggler population in 47 Tucanae gives the first detailed characterization of their spatial distribution in the cluster over its entire volume. Relative to the light distribution, blue stragglers appear to be overabundant in the core and at large radii. The observed surface density profile shows a central peak, a zone of avoidance and a rise beyond twenty core radii. In light of these findings we explored the evolution of blue stragglers mimicking their dynamics in a multi-mass King model for 47 Tucanae. We find that the observed spatial distribution can not be explained within a purely collisional scenario in which blue stragglers are generated exclusively in the core through direct mergers. An excellent fit is obtained if we require that a sizable fraction of blue stragglers is generated in the peripheral regions of the cluster inside primordial binaries that evolve in isolation experiencing mass-transfer.

Subject headings: stars: blue stragglers - binaries: general - globular clusters: individual (47 Tuc)

1. INTRODUCTION

Blue Stragglers (BSs), first discovered by Sandage in the globular cluster M3, are stars lying above and blue-ward of the turn-off point in a cluster color-magnitude diagram. In recent years the high angular resolution and the UV imaging capabilities of the *Hubble Space Telescope* (HST) have made possible the search of BSs even in the cores of highly concentrated globular clusters (GCs). Observations indicate that BSs in GCs are preferentially found in the core (Ferraro et al. 1999a); but in at least two GCs, M3 (Ferraro et al. 1993; Ferraro et al. 1997) and M55 (Zaggia et al. 1997) BSs are seen also in the external region of the GC. Ferraro et al. (2003b) have recently found that the radial distribution of BSs in 47 Tuc also appears bimodal, i.e. highly peaked in the core, decreasing at intermediate radii and rising again at larger radii. A long standing problem is the formation mechanism of BSs. Many scenarios have been proposed to explain the BS origin (Fusi Pecci et al. 1992; Bailyn 1995; Bailyn and Pinsonneault 1995; Procter Sills, Bailyn & Demarque 1995; Sills & Bailyn 1999; Sills et al. 2000; Hurley et al. 2001) and two seem to be the most likely ones. The first, i.e., the *collisional scenario*, indicates that BSs are the end-product of a prompt merger between two main sequence stars in a direct collision that involves a (resonant) three or four body encounter (Davies, Benz & Hills 1994; Lombardi et al. 2002); these BSs acquire kicks generated by dynamical recoil. The second, or *mass-transfer scenario*, suggests that BSs are generated in primordial binaries (hereafter PB) that evolve mainly in isolation or harden gently by long-distance gravitational encounters until they reach contact, leading to (unstable) mass-transfer and final coalescence (Carney et al. 2001). In both these mechanisms BSs are formed with a mass exceeding the turn-off mass of the cluster and can stay on the main sequence

through the mixing of the hydrogen-rich surface layers of its two progenitor stars. These two scenarios do not necessarily exclude each other and may coexist (Leonard 1989; Fusi Pecci et al. 1992; Bailyn & Pinsonneault 1995; Ferraro et al. 1997; Sills & Bailyn 1999; Hurley et al. 2001). Indeed, bimodal BS radial distributions seem to invite the invocation of two mechanisms: the BSs in the core are principally created by star collisions, while external BSs are formed from mass-transfer in PBs. Still Sigurdsson, Davies & Bolte (1994) suggested that the bimodal population in M3 might be entirely explained within a collisional model where external BSs are formed in the core and ejected into the outer regions by recoil. However, further studies of the BS luminosity function and their comparison with theoretical models (Bailyn & Pinsonneault 1995; Sills & Bailyn 1999; Sills et al. 2000; Ferraro et al. 2003b), highlight the difficulty, if not the impossibility, to obtain a good fit of the observations assuming that all the BSs are formed dynamically in the core. In this paper we study, in the light of the most recent data (Ferraro et al. 2003b), the case of 47 Tuc, comparing the observed bimodal distribution of BSs with a series of simulations carried on using a new version of the dynamical code described in Sigurdsson & Phinney (1995).

2. DESCRIPTION OF THE DYNAMICAL CODE

The code simulates a fixed cluster background with a multi-mass King density profile (we choose 10 classes of mass, see Table 1 and section 2 of Sigurdsson & Phinney 1995) obtained imposing a stellar velocity dispersion (for a mono-mass cluster) $\sigma = 11.5\,\mathrm{km\,s^{-1}}$ and a central density $\rho_0 = 1.26 \times 10^5\,M_\odot\,\mathrm{pc^{-3}}$ (Pryor & Meylan 1993). The observed profile has been obtained using the data-set published by Ferraro et al. (2003b) and the procedure described in Ferraro et al. (2003c). Additional

[1]S.I.S.S.A., Via Beirut 2 - 4, I-34014 Trieste, Italy; mapelli@sissa.it

[2]Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802; steinn@astro.psu.edu

[3]Dipartimento di Fisica G. Occhialini, Università di Milano Bicocca, Piazza della Scienza 3. I-20126 Milano, Italy; monica.colpi@mib.infn.it

[4]Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, I–40126 Bologna, Italy; ferraro@bo.astro.it

[5]Osservatorio Astronomico di Cagliari, Cagliari, Italy; possenti@ca.astro.it

[6]Astronomy Dept., University of Virginia, Charlottesville, VA 22903-0818, USA; rtr@virginia.edu

[7]Department of Physics and Astronomy, McMaster University, 1280 Main Street West, Hamilton, ON, L8S 4M1, Canada; asills@mcmaster.ca

HST Archive data in the *V* band have been used to combine the HST and the ground based dataset. All the stars brighter than the cluster Main Sequence Turn-Off ($V < 18$) have been used to compute the projected density profile. Fig. 1 shows the comparison between observed and modeled projected density profile. This model has a concentration $c = 1.95$, and a core radius $r_c = 21''$. A typical uncertainty of $\pm 2''$ can be assumed in the r_c determination. Note that the value assumed for 47 Tuc is consistent with that ($r_c = 23'' \pm 2''$) obtained by Howell, Guhathakurta & Gilliland (2000). Assuming a distance of 4.6 kpc (Ferraro et al. 1999b), the core is $r_c = 0.42$ pc. The dimensionless central potential is $W_0 = 12$ ($W_0 \equiv \Psi(0)/\langle \sigma \rangle^2$, where $\langle \sigma \rangle$ is the mean core dispersion velocity, $\Psi(0) \equiv \Phi(r_t) - \Phi(0)$, with $\Phi(r)$ the gravitational potential and r_t the tidal radius (Sigurdsson & Phinney 1995).
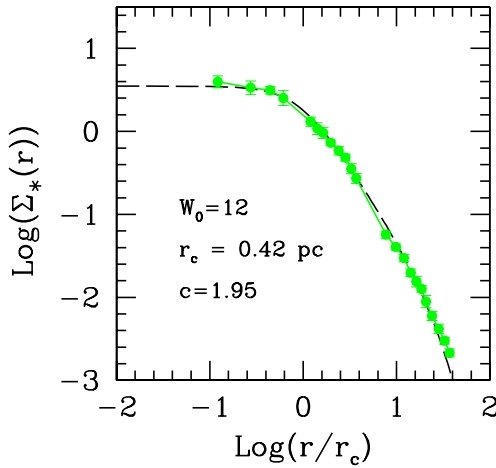

Fig. 1: Comparison between the observed surface density profile of 47 Tuc (solid line and full circles) and the adopted King model (dashed line).

On this background we evolve the dynamics of BSs. We assume that collisional BSs are generated exclusively in the innermost region, at radii less than $n r_c$, with $n \leq = 0.1$, 0.5 and 0.8, where the density is high to guarantee a high collision rate (Pooley et al. 2003). Internal BSs generated in PBs have been explored as last case and may be considered as extreme since dynamical interactions in dense cluster cores tend to destroy binaries and to alter those that remain through exchanges (Sigurdsson & Phinney 1993; Ivanova et al. 2004). External BSs formed in PBs are generated outside the core with initial positions distributed in several radial intervals, between 15 and 80 r_c. All initial positions are randomly generated following a flat probability distribution (see Table 1) according to the fact that the number of stars in a King model scales as $dN = n(r) dV \propto r^{-2} \pi r^2 dr \propto dr$. This is the key difference between our simulations and those of Sigurdsson et al. (1995), who generated BSs only in the central region (below 0.8 r_c). BS velocities are randomly generated following the distribution illustrated in section 3 of Sigurdsson & Phinney 1995 (eq. 3.3). In addition, we assign a natal kick to those BSs formed collisionally in the core: kick velocities fall in between 1 and

6 σ, and their distribution is flat or single valued. The masses of BSs are generated between 1.2 and 2 $M_\odot$, following indications from Ferraro et al. (1997) and Gilliland et al. (1998). Every single BS is evolved for a time $t_i = t_{last} * rand$, where *rand* is a random number uniformly generated in [0,1] and t_{last} is the lifetime assumed for a BS (we have performed sets of runs with various t_{last}, between 1 and 5 Gyr). Once generated, the BS drifts in the cluster background under the action of the cluster potential, dynamical friction and distant encounters (eq. [3.4] of Sigurdsson and Phinney 1995). Near encounters are uninfluent.

3. RESULTS

We performed more than 70,000 runs testing various scenarios. We first traced the BS evolution in the collisional hypothesis (Sigurdsson et al. 1994). We generated BSs at radii less than 0.8 r_c with recoil velocities in various ranges. We observed that for recoil velocities greater than 3.5 σ BSs are expelled from the cluster, while for recoil velocities lower than 3 σ dynamical friction drags all of the BSs into the core in $\sim 10^8$ years. The final simulated distribution, shown in Fig. 2a, is peaked in the center, but does not reproduce the observed rise in the outer region of the GC. Thus, no collisional BSs ejected from the core by recoil contribute to the external population. The best representation of the data is obtained generating 25% of the BSs from mass-transfer in PBs between 30 and 60 r_c with no kick, and 75% from collisions inside 0.5 r_c with a natal kick of 1 σ (see Fig. 2b).
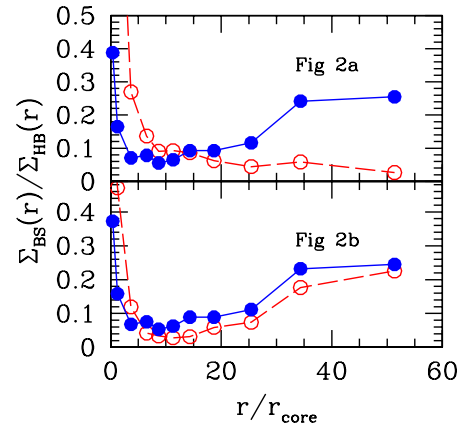

Fig 2: Comparison between the observed BS surface density (solid line with filled circles) and the simulated BS surface density (dashed line with empty circles), in the case of BS formation by collisions only with constant kick = 3.5 σ (Fig. 2a), and in the case of BS formation both by collisions (with constant kick = 1 σ) and primordial binary mergers with BS lifetime of 1.4 Gyr (Fig. 2b). Both the distributions are normalized with respect to the number of Horizontal Branch stars (HB) cataloged by Ferraro et al. (2003b).

Another key parameter to understand BS evolution is their lifetime. We performed simulations with various lifetimes t_{last} (1, 2, 3, 4, 5 Gyr). We integrated the evolution of every single BS for a time homogeneously distributed between 0 and t_{last}, assuming that BSs are uniformly generated over the cluster lifetime, without peaks of formation. In absence of different indications this seems to be a reasonable assumption (Sigurdsson et

al. 1994). We obtained the best representation for $t_{last} = 1.4 - 1.5$ Gyr. For $t_{last} < 1.4$ Gyr the number of BSs out of 60 r_c is at least twice the observed value. For $t_{last} > 1.4$ Gyr, dynamical friction reduces the amplitude of the external rise in BSs and tends to create a secondary "hump" of BSs, which drifts toward the core (Fig. 3). At 5 Gyr this hump peaks at 15 r_c, just inside the observed depletion region. We performed also a set of runs where we impose that BSs are all generated solely in PBs, between 0 and 60 r_c (imposing that 48% of BSs are generated below 1 r_c and 52% above 1 r_c) with no kick. Fixing t_{last}=1 Gyr, we found a BS distribution close to the observed but with a weaker rise above 30 r_c.
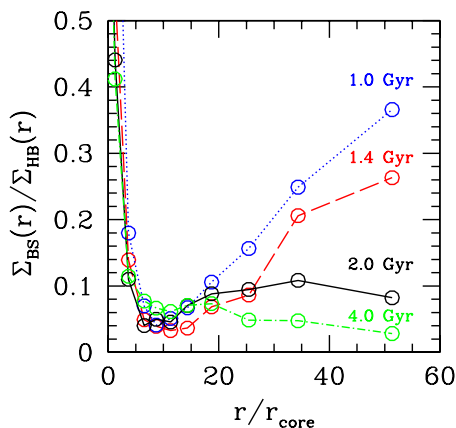

Fig. 3: Simulated BS surface density at 1 Gyr (dotted line), 1.4 Gyr (dashed line), 2 Gyr (solid line) and 4 Gyr (dashed-dotted line) for the same range of initial positions (30-60 r_c), initial velocities and masses (1.2–1.8 $M_\odot$).

4. THE ZONE OF AVOIDANCE

Our simulations show that all the external BSs are formed by PBs beyond 30 r_c in order to reproduce the spatial distribution with its zone of avoidance. Thus we may ask if the external regions of 47 Tuc host a number of binaries sufficient to produce all the observed peripheral BSs and if these massive binaries survive in these regions for ~ 12 Gyr (approximately the lifetime of the cluster) without drifting toward the center under the action of dynamical friction. Unfortunately, there is no direct observational guidance to answer this question. The only study of binaries in 47 Tuc is that of Albrow et al. (2001) who searched for binaries only in the central regions of 47 Tuc. They found a binary frequency of 14% ± 4% in the core of the cluster. However, the binary fraction in the core, where binaries are created or destroyed, or modified in their properties by exchange interactions, does not provide a direct measure of the number of all truly PBs over the whole cluster. Recent studies by Ivanova et al. (2004) indicate that the bulk of PBs remain in the outskirts of the GC. Searches of PBs (Rubenstein & Bailyn 1997 for NGC 6752, and Bellazzini et al. 2002 for NGC 288) are still limited to cluster cores. Some indication may come from our simulated cluster model that can provide us the mass of the cluster out of a certain radius. We found that the mass beyond 30 r_c is $6.4 \times 10^5 M_\odot$. We can only guess what fraction of that mass is in binaries, but an assumption that 10% of the mass was originally in binaries is not unreasonable. This gives

$6.4 \times 10^4 M_\odot$ in binaries or at least $3-6 \times 10^4$ binaries beyond 30 r_c. Hurley, Tout & Pols (2002) estimate a probability of 5×10^{-4} for a binary to generate a BS at 12 Gyr (see model F). This implies that our estimated $3-6 \times 10^4$ PBs beyond 30 r_c can produce 15-30 BSs - close enough to the 25 required outside 20 r_c (Ferraro et al. 2003b). Recently, Ivanova et al. (2004) indicate that a sizable number of binaries survive in the halo (65%) and only a few percent (5%) in the core of a simulated 47 Tuc like GC, assuming an initial binary fraction of 100%. If these figures apply, about 100-200 BSs should reside in the halo of 47 Tuc which are not seen; This could be reconciled only if most of them are faint such to be confused with normal stars. However, observational studies indicate that the binary fraction tends to be lower in the halo than in the core (see for example Rubenstein & Bailyn 1997).

Two questions now remain: what mechanisms produce the zone of avoidance ? Can PBs survive in the external regions for a time comparable to the age of the cluster without drifting toward the core by dynamical friction ? We have calculated the distance from the GC center out of which the dynamical friction timescale t_{DF} is longer than the typical age of a PB of 47 Tuc (~ 12 Gyr). For a BS moving on a circular orbit (Binney & Tremaine 1987)

$$t_{DF} = \frac{3}{4\ln(\Lambda)G^2(2\pi)^{1/2}} \frac{\sigma^3}{M \rho(r)} \qquad (1)$$

where $\ln(\Lambda) \sim 10$ is the Coulomb logarithm, σ the line of sight mean stellar dispersion velocity ($= 11.5 \, \text{km s}^{-1}$), M the mass of a typical BS ($= 1.5 M_\odot$) and $\rho(r)$ the local mass density at distance r from the GC center. We found that the density at which $t_{DF} = 12$ Gyr is $\rho(r) \sim 120 M_\odot \, \text{pc}^{-3}$. This corresponds to a distance of $\sim 9 r_c$, as inferred from our King model, which is near the position of the zone of avoidance. In the case of eccentric orbits t_{DF} can be significantly shorter (Colpi, Mayer, & Governato 1999) and this opens the possibility that PBs accrete to the core from outer distances. By running simulations that trace the orbital evolution of PBs in the GC potential with semi-major axis $a \gtrsim 30 r_c$, eccentricity $e \gtrsim 0.7$ and total mass 1.2–2 $M_\odot$, we found that in most of our runs PBs born at $\sim 60 r_c$ with eccentricity $e = 0.7$ have still a semimajor axis $a \sim 30 r_c$ after 12 Gyr. This suggests that the existence of a gap in the spatial distribution of the BSs comes from the interplay between the dynamical friction timescale (with its spread related to a spread in the orbital parameters) and the characteristic lifetime of the BS.

5. SUMMARY

The comparison of the observed BS distribution in 47 Tuc with the simulated distributions supports the hypothesis that internal BSs principally result from stellar collisions, while external BSs (outside of 20 r_c) are exclusively generated by mass-transfer in PBs. The best fit to the observational data of 47 Tuc is obtained when a sizable fraction (25%) of BSs is generated from PBs in peripheral regions ([30,60] r_c). The internal BSs contributing up to 75% of the observed are all born inside 0.5 r_c with a natal kick of 1 σ, and do not pollute the external regions. External BSs contribute little to the core population. A scenario in which all BSs are generated over the entire cluster by mass-transfer in PBs can not be ruled out. We believe however that a blending between collision induced evolution and internal evolution is at play in the GC core to explain internal BSs. Our main finding is the need of a population of external PBs in or-

der to generate the bimodal distribution of the BSs observed in 47 Tuc. The required fraction (10%) to fit the data does not seem unreasonable. More accurate counts of BSs in GCs with widely different properties are about to be collected from high resolution photometry (Ferraro et al. 2004 in preparation). These observations may shed light into the nature of BSs and the importance of PBs in GC evolution. In light of these upcoming observations, in paper II (Mapelli et al. in preparation), we plan to continue our analysis with our simulations over a wide sample of GCs. Theoretical studies using N-body (Baumgardt & Makino 2003) or Monte Carlo techniques (Ivanova et al. 2004) will eventually become necessary tool for exploring the formation and evolution of BSs in GCs.

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TABLE 1

PROBABILITY DISTRIBUTIONS OF INITIAL CONDITIONS.

Variable	Range	Probability Homogeneous in
Mass of the background stars[a]	$[0.1, 25]\,M_\odot$	Salpeter IMF
Initial Position[b] (r)	...	r
Initial Velocity (v)	$[0, \infty]$	velocity distribution in eq. 3.3 of Sigurdsson & Phinney (1995)
ϕ^d	$[0, 2\pi]$	ϕ
θ^d	$[0, \pi]$	$\cos\theta$
BS Mass	$[1.2, 2]\,M_\odot$	Salpeter IMF[c]
BS Lifetime (t)	$[0, t_{last}]$	t

[a]We consider 10 mass group, with upper limit for the mass respectively: 0.157, 0.20, 0.25, 0.31, 0.39, 0.60, 0.70, 0.80, 1.32, 1.57 $M_\odot$.
[b] The range of initial positions depends on the single set of runs.
[c] The Salpeter IMF is used to random generate each member of the binary progenitor of the BSs.
[d] Angles used to random generate the components of the initial position and of the initial velocity of BSs.

TABLE 2

SIMULATED MODELS.

Set of runs:	Initial positions (r_c)	Lifetime (Gyr)	BS Mass ($M_\odot$)	BS fraction within 20 r_c	BS fraction out of 20 r_c	Fraction of Escaped BSs
CASE A	[0,0.5] & [30,60]	1	[1.2,1.8]	0.80	0.11	0.09
CASE B	[0,0.5] & [30,60]	1.3	[1.2,1.8]	0.83	0.11	0.06
CASE C	[0,0.5] & [30,60]	1.4	[1.2,1.8]	0.79	0.12	0.09
CASE D	[0,0.5] & [30,60]	1.5	[1.2,1.8]	0.82	0.11	0.07
CASE E	[0,0.5] & [30,60]	2	[1.2,1.8]	0.86	0.09	0.05
CASE F	[0,0.5] & [30,60]	3	[1.2,1.8]	0.88	0.05	0.07
CASE G	[0,0.5] & [30,60]	4	[1.2,1.8]	0.88	0.05	0.07
CASE H	[0,0.5] & [30,60]	5	[1.2,1.8]	0.90	0.03	0.07
CASE I	[0,0.5] & [20,60]	2	[1.2,1.8]	0.90	0.07	0.03
CASE L	[0,0.5] & [40,60]	2	[1.2,1.8]	0.84	0.07	0.09
CASE M	[0,0.8]	1	[1.2,1.8]	0.84	0.02	0.14
CASE N	[0,0.5] & [30,60]	2	[1.2]	0.81	0.10	0.09
CASE O	[0,0.5] & [30,60]	2	[2.0]	0.83	0.08	0.09
CASE P	[0,60]	1	[1.2,1.8]	0.74	0.14	0.12
DATA	—	—	—	0.75	0.25	?